# CHEMISTRY AND PHYSICS SUGGEST A SOUP UNDER ENCELADUS' SOUTH POLE

**By Emily Lakdawalla**
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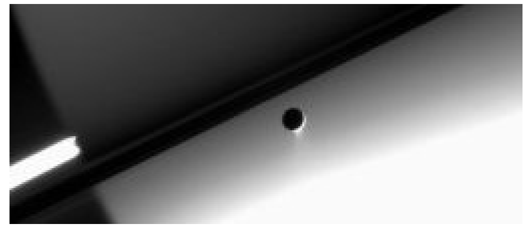
**Enceladus may now be on the short list of bodies in the solar system that probably have the water, energy, and chemistry necessary to support Earthlike life. Two recent studies in the journal *Icarus* hint at "soup" and a "sea" underlying the geologically active south pole of Enceladus. In the first, "Enceladus' plume: Compositional evidence for a hot interior," Dennis Matson and his coauthors find that the likeliest explanation for the composition of the stuff spewing from Enceladus' vents includes catalytic chemistry taking place in warm fluids circulating in Enceladus' rocky interior. In the second, "Enceladus' south polar sea," Geoff Collins and Jason Goodman explain the observed shape of Enceladus by modeling a huge body of liquid water underlying the south pole. Taken together, the two papers suggest that the deep interior of Enceladus could harbor conditions favorable to life.**



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**Enceladus and Saturn**
In a composition that looks like a work of geometric abstract art, Enceladus and its south polar geysers are silhouetted against the bulk of Saturn. The viewing geometry is of the night sides of both bodies. Saturn's southern hemisphere is lit by reflected light from its rings, which make the dark diagonal stripe across the image. Light from the Sun coming from nearly behind Saturn and Enceladus lights up the fingers of Enceladus' plumes. The image was acquired on May 4, 2006. Credit: NASA / JPL / SSI

Prior to Cassini's arrival in the Saturn system, it was theorized that geologic activity on Enceladus might be the source of the particles in Saturn's tenuous, icy E ring. In 1981, Voyager 2 images of Enceladus had revealed that part of the moon had a craterless, wrinkly surface, hinting at recent geologic activity. Cassini found an atmosphere above an anomalously warm region at the south pole during three close flybys in early 2005. Later that year, Cassini took photos of Enceladus with the Sun lighting it from behind, and photographed fountains of water vapor emanating from the south pole. Scientists are now trying to understand what the images and data that record conditions on Enceladus' surface imply for processes going on in its interior.


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## RECIPE FOR ENCELADAN SOUP

Matson et al.'s arguments proceed from observations by Cassini's Ion and Neutral Mass Spectrometer (INMS) of the composition of the plumes emanating from Enceladus' south pole. They are especially interested in the origin of four chemicals: nitrogen gas ($N_2$), which makes up about four percent of the plumes; methane ($CH_4$), which makes up less than two percent; and two hydrocarbons, acetylene ($C_2H_2$) and propane ($C_3H_8$), both found in trace amounts.

| The composition of Enceladus' geysers (as measured by Cassini's INMS) | |
|---|---|
| Water ($H_2O$) | 91 ± 3% |
| Nitrogen ($N_2$) and/or carbon monoxide (CO) | 4 ± 1% |
| Carbon dioxide ($CO_2$) | 3.2 ± 0.6% |
| Methane ($CH_4$) | 1.6 ± 0.4% |
| Other: | trace (<1%) |

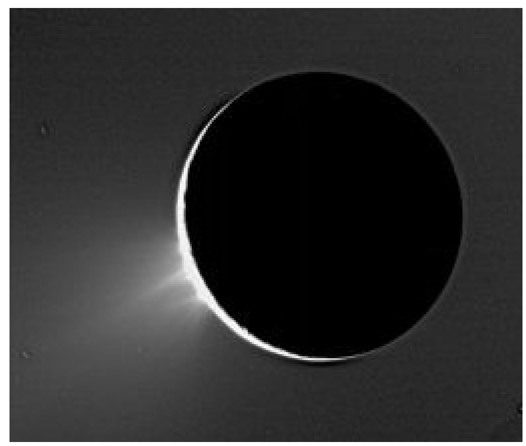
| | |
|---|---|
| Ammonia ($NH_3$)<br>Acetylene ($C_2H_2$)<br>Hydrogen cyanide (HCN)<br>Propane ($C_3H_8$) | |

There are two ways that any substance could end up in the interior of Enceladus, or any of Saturn's other moons: either they have been there since the moons formed, or they were created as a result of chemical reactions taking place in the moons' interiors. Matson et al. reason that since both Enceladus and Titan formed from the same disk around Saturn, they both probably came by their nitrogen in the same way. Other studies have suggested that nitrogen gas at Titan is not primordial, but instead has been produced from chemical reactions that start with primordial ammonia ($NH_3$). These chemical reactions need heat in order to work, temperatures between 575 and 850 Kelvin (300 and 575 Celsius or 575 and 1,075 Fahrenheit).

There is less evidence to suggest whether the methane coming out of Enceladus was there in the beginning or formed later. However, Matson et al. argue, if it were warm enough to make nitrogen gas from ammonia, the same conditions would favor chemical reactions that produce methane from carbon monoxide or carbon dioxide.

So the presence of nitrogen and methane suggest that Enceladus' interior was warm. Acetylene and propane lead to another exciting conclusion: that chemical reactions were taking place that required liquid water to be in contact with warm rocks, allowing metals and minerals in the rocks to catalyze the chemical reactions. To make acetylene directly from methane requires very high temperatures, above 1,773 Kelvin (1500 Celsius, 2,732 Fahrenheit). This seems an implausibly high temperature for the interior of Enceladus, so Matson et al. suggest that longer-chain hydrocarbons are first formed from methane and are then "cracked" to make acetylene. The reactions that make longer-chain hydrocarbons from methane require catalysts such as metals or clay minerals, but can proceed at more moderate temperatures.

If catalytic chemistry inside Enceladus has produced acetylene and propane in an environment where there is also nitrogen moving around, then there could have been other chemical reactions producing even more complex organic molecules, such as amino acids. Enceladus' geysers could be spewing these into space, Unfortunately, Cassini's INMS instrument is not sensitive enough to detect these compounds at the low concentrations at which they may be present, nor can it detect molecules larger than 99 atomic mass units. So the suggestion that Enceladus could be making amino acids will remain only a hypothesis until a new, more sensitive detector is sent there. However, Cassini's very close flyby planned for March 12, 2008 will allow INMS to sample the plumes directly, where it could find evidence for other small compounds of oxygen, hydrogen, and carbon that could support the hypothesis of catalytic chemistry.



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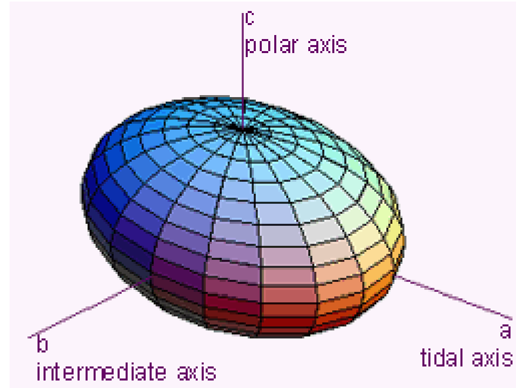
**Fountains of Enceladus**
On November 27, 2005, Cassini captured a series of images of Enceladus from its night side. The back-lit view lights up fine particles streaming from Enceladus' south-polar geysers. Most of the vented material is water, but there are smaller quantities of many other chemicals. Credit: NASA / JPL / Space Science Institute

Where would all these chemical reactions be taking place? The scenario requires warm temperatures, liquid water, and rocks to catalyze the reactions, so Matson et al. suggest that the reactions happened in water moving through cracks in the rock near the boundary between Enceladus' icy mantle and rocky core.

One important detail that the Matson et al. study cannot resolve is the question of *when* this interesting chemistry was happening. It is tempting to assume that the reactions are taking place now in an active interior, but it is also possible that the catalytic chemistry could have happened long ago, and the present geologic activity is simply venting the already-existing chemical products to space in a process that doesn't require such high temperatures. But a different study suggests that, in fact, Enceladus does currently have heat and liquid water in contact with a rocky core, exactly the environment that Matson et al. predict.

### A Sea Sloshing Under the Pole

Collins and Goodman used a different clue from Enceladus' outside to peek into its interior: its shape. The physics of gravity and centrifugal force dictate the shape of any spinning body. Although Enceladus is smooth and round, like all spinning globes it is fatter measured across its equator than pole to pole. In addition, Enceladus is (like most moons in the solar system) locked into synchronous rotation with its planet. Because it keeps the same face pointed toward Saturn at all times, there are permanent tidal bulges on the equator, one pointed at the planet and one pointed away from the planet. As a result of all of these forces, Enceladus' shape can be approximated by a triaxial ellipsoid that is longest along the tidal axis (the equatorial axis pointed toward Saturn), intermediate along an equatorial axis perpendicular to the tidal axis, and shortest along the polar axis.

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**Triaxial ellipsoid**

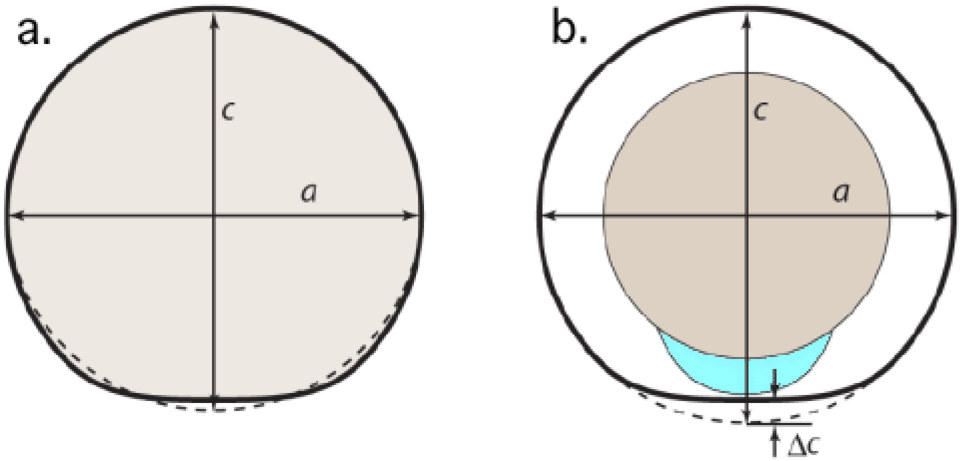
The shapes of many bodies in the solar system can best be approximated by a triaxial ellipsoid, with diameters of three different lengths. For moons locked in synchronous rotation with their planets, the longest axis (a) is the tidal axis, which points toward the planet. The shortest axis (c) is the polar axis. This shape results from two balanced forces: the centrifugal force of the moon's spin (which shortens its polar axis and lengthens its equatorial axes) and the gravitational pull of the planet (which raises tidal bulges at the equator pointed toward and away from the planet).

In the real world, few moons are quite as ellipsoidal as this simple theory would predict, because they tend to be *differentiated*: their component materials of metal, rock, and ice have separated, concentrating denser materials toward their centers in a rocky core, and less dense materials near the surface in an icy mantle. With mass concentrated toward the center, neither the rotational nor the tidal bulges are as large; in other words, differentiated bodies are more spherical than undifferentiated bodies.

Employing this analysis on the measured shape of Enceladus in a study published last year, Carolyn Porco and the Cassini imaging team found that Enceladus is actually quite flattened pole-to-pole, so that when this basic gravitational and rotational physics was taken into account, its observed shape was best fit by an undifferentiated interior. There was some misfit to the model, but concentrating mass toward the center would actually make the fit worse. They concluded that either Enceladus was not differentiated or that its shape was not in equilibrium. They further noticed that the poorest fits of this simple model to the shape of Enceladus was at the south pole, which had an elevation lower than the theoretical shape, and at a latitude of 50 degrees south, where the actual elevation was higher than theoretical.

| The shape of Enceladus | |
|---|---|
| **Axis** | **Observed length** |
| tidal axis (a) | 256.6 ± 0.5 km |
| intermediate axis (b) | 251.4 ± 0.2 km |
| polar axis (c) | 248.3 ± 0.2 km |

The south pole is also where Enceladus is venting huge amounts of heat. Collins and Goodman theorized that these two clues -- the low elevation and high heat flow -- suggest that there might be a large pool of melt beneath Enceladus' south pole. They developed a computer model of a differentiated Enceladus, incorporating its density, temperature, and other physical parameters, and then heated it, with the heat focused at the base of the ice layer under the south pole. They found that their model could, in fact, produce a stable south polar "sea", reaching from the boundary between the rocky core and icy mantle to within roughly 10 kilometers (6 miles) of the surface, and extending from the pole to roughly 50 degrees south.

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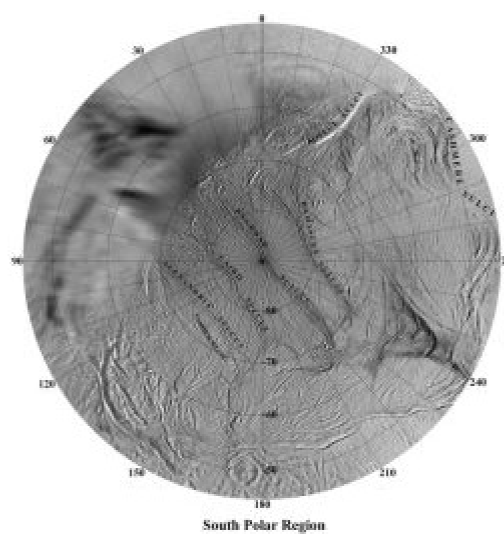
**Two models of Enceladus' internal structure**

a. This diagram is based upon a mathematical model for Enceladus' shape in which the moon is assumed to be undifferentiated (its icy and rocky components are homogeneously mixed). Enceladus' observed shape is found to fit this model somewhat, but there is a large deviation at the south pole, where its actual elevation is lower, and at 50°S, where its actual elevation is higher. b. In a model proposed by Geoff Collins and Jason Goodman, Enceladus is internally differentiated, with a rocky core (gray) and icy mantle (white). There is a large south polar sea (blue) caused by heating and melting at the base of the mantle under the south pole. The melting of the ice produces a pit, shortening the south polar axis by some amount (Δc), which flattens the south pole, leading to the observed shape deviations. Credit: Geoff Collins and Jason Goodman

How does a south polar sea explain the observed shape of Enceladus? Liquid water is denser than ice; when Enceladus' icy mantle melts to make the liquid sea, the effective result is that the moon's surface sinks over that sea by quite a lot, from 2.3 to 3.3 kilometers, depending upon the initial choices of physical parameters for Enceladus' internal properties. Collins and Goodman's model predicts a pole-flattened shape for Enceladus that is a better fit to observations, and suggests that Enceladus is, in fact, differentiated, with a rocky core (of density 2.6 grams per cubic centimeter), and a solid, icy mantle that has melted underneath the moon's south pole.

Collins and Goodman suggest two important sets of data that could test their south polar sea hypothesis. First, determining the gravity field of Enceladus would prove or disprove the prediction that Enceladus is internally differentiated. Second, determining its detailed shape could map out the topographic highs and lows predicted by the physics of the mathematical model. Cassini has already performed three of four close flybys of Enceladus planned for the primary mission, but there are seven more flybys planned for the two-year extended mission.

The shape of Enceladus can be pinned down from repeated photography of the moon's limb from different angles; and there will certainly be plenty of Enceladus images returned from these flybys. Gravity data is more difficult to come by. In order to determine the gravity field of a body, Cassini must fly close by the moon while broadcasting a signal from its high-gain antenna toward Earth, so that the radio antennas of the Deep Space Network can perform precise Doppler tracking of its position. Acquiring gravity data usually precludes the acquisition of data from most of Cassini's other instruments, a heartbreaking tradeoff. Since gravity data represents the most direct measurements of what's going on inside Enceladus that Cassini can acquire, at least some parts of some of those seven flybys will be devoted to radio tracking, but exactly how much has not yet been decided.

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**Enceladus' south pole**

A ring of tectonic features that surrounds the sulci or "tiger stripes" crossing Enceladus' south pole

These two different studies suggest that Enceladus' interior is both warm and wet. Chemical processes seem to be generating long-chain hydrocarbons. Cassini's eleven total flybys of the moon will produce mountains of data on its surface, its geysers, and its interior, but the data will probably generate as many questions as it does answers, questions that can only be answered by a future mission dedicated to this tiny, active world.

that would have been generated by the melting of Enceladus' south polar sea and the flattening of its south pole. Credit: NASA / JPL / SSI / map by Steve Albers